Radar tomography of bridge decks

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ABSTRACT

This paper presents the development of ground-penetrating radar bridge deck inspection systems sponsored by the Federal Highway Administration. Two radar systems have been designed and built by Lawrence Livermore National Laboratory. The HERMES bridge inspector (High-speed Electromagnetic Roadway Mapping and Evaluation System) is designed to survey the deck condition during normal traffic flow. Thus the need for traffic control during inspection is eliminated. This system employs a 64 channel antenna array covering 1.9 m in width with a sampling density of 3 cm. To investigate areas of a bridge deck that are of particular interest and require detailed inspection a slower, cart mounted radar has been produced. This system is named PERES (Precision Electromagnetic Roadway Evaluation System). The density of data coverage with PERES is 1 cm and an average of 100 samples is taken at each location to improve the signal to noise ratio. Images of the deck interior are reconstructed from the original data using synthetic aperture tomography. The target of these systems is the location of steel reinforcement, corrosion related delaminations, voids and disbonds. The final objective is for these, and other non-destructive technologies, to provide information on the condition of the nation's bridges so that funds will be spent on the structures in most need of repair.

Keywords: bridge deck, concrete, non-destructive, ground-penetrating radar, impulse radar, antenna array, synthetic aperture, tomography.

1. INTRODUCTION

The bridge stock in the US, and around the world, is aging and having to cope with increasing traffic volume. Maintenance and rehabilitation of the structures is inevitably required. However, the internal state of degradation is usually unknown and therefore it is not clear where to direct repair funds. In addition problems in bridge construction may arise, placing a new structure in need of assessment. Inspection techniques are then necessary to non-destructively determine quantitative data on the internal condition of bridges. The ability to detect and assess deterioration is critical in directing maintenance to the most at risk bridges. To address this need the Federal Highway Administration (FHWA) is pursing a program of research and development of non-destructive evaluation methods.[1]

Of the major bridge components the deck, is the most subject to wear and in need of rehabilitation or replacement. Reinforced concrete bridge decks may require replacement every 15 to 20 years[2] and therefore an inspection system is a high priority amongst highway engineers. The FHWA is sponsoring the development of two deck inspection systems based on radar, the work is being undertaken by Lawrence Livermore National Laboratory (LLNL). The systems use LLNL 'micro-power impulse radar'[3] which arose as an offshoot from a laser research program. To survey an entire lane of a bridge without disturbing normal traffic flow the HERMES bridge inspector[4] (High-speed Electromagnetic Roadway Mapping and Evaluation System) has been developed. For more detailed examination of specific areas a cart mounted radar system named PERES (Precision Electromagnetic Roadway Evaluation System) has been produced. These systems have primarily been designed to detect corrosion induced delaminations in the deck, however, the mapping of steel reinforcement, location of voids, unconsolidated concrete and disbonds are other capabilities of the systems.

Radar was first used for subsurface investigation in the search for buried objects, determination of subterranean geology or study of ice depths. Its geological usage has led to the name 'ground-penetrating radar' (GPR), however, the more generic term 'impulse radar' is an alternative. Application of impulse radar within civil engineering has been diverse; from the study of pavement layer thickness[5], inspection of pipelines[6] to the investigation of scour around bridge piers.[7] From a more theoretical viewpoint civil engineering laboratory studies have been undertaken to evaluate the propagation of radar signals through concrete.[8] The potential of the technique for the subject of this paper, highway bridge decks, has been demonstrated in a number of past works.[9,10,11]

2. THE BRIDGE DECK INSPECTION SYSTEMS

The LLNL impulse radar bridge deck inspection systems use ultra-wide band microwave sources which produce signals with a frequency content ranging from 0.5 to 5 GHz. Air-coupled transmit and receive horn antennas form the transceivers. Equivalent-time sampling of successive signals is used to 'slow down' and construct the returned signals. The radar pulse is fired from each antenna at a repetition rate of 5 MHz. Each time the signal is received it is sampled successively further out in time using a swept-range gate. The interval between sampled points depends on the number of times every antenna is fired (256, 512 or 1024) and the time-range over which measurements are required. A range of around 6 ns is suitable to penetrate 30 cm of concrete giving a sampling interval of 23 ps for 256 repetitions of the pulse.

2.1 Description of the HERMES bridge inspector

The HERMES bridge inspector is shown in Fig. 1. The system is designed to launch high frequency electromagnetic pulses into a bridge deck while moving over the surface. The radar system may be controlled from the towing vehicle using a laptop computer. The interior of the HERMES trailer is illustrated in Fig. 2 which shows the computer workstation, radar electronics and antenna array.

Fig. 1 The HERMES bridge inspector trailer and towing vehicle.

Fig. 2 The interior of the HERMES trailer.

A block diagram illustrating the design of the HERMES bridge inspector is given in Fig. 3. The system comprises of a computer workstation and storage device, survey wheel, control electronics and array of 64 antenna modules or transceivers. A basic overview of the system follows: The survey wheel informs the master controller when to trigger the radar. The master controller signal is sent to one of the eight radar modules designated by the array controller which acts as a multiplexor. The radar module then generates the pulse to be transmitted which is multiplexed to one of the eight antenna pairs in the bank. [2]The signal detected at the receiver antenna is then digitized within the radar module and sent to the computer via the array controller and master controller.

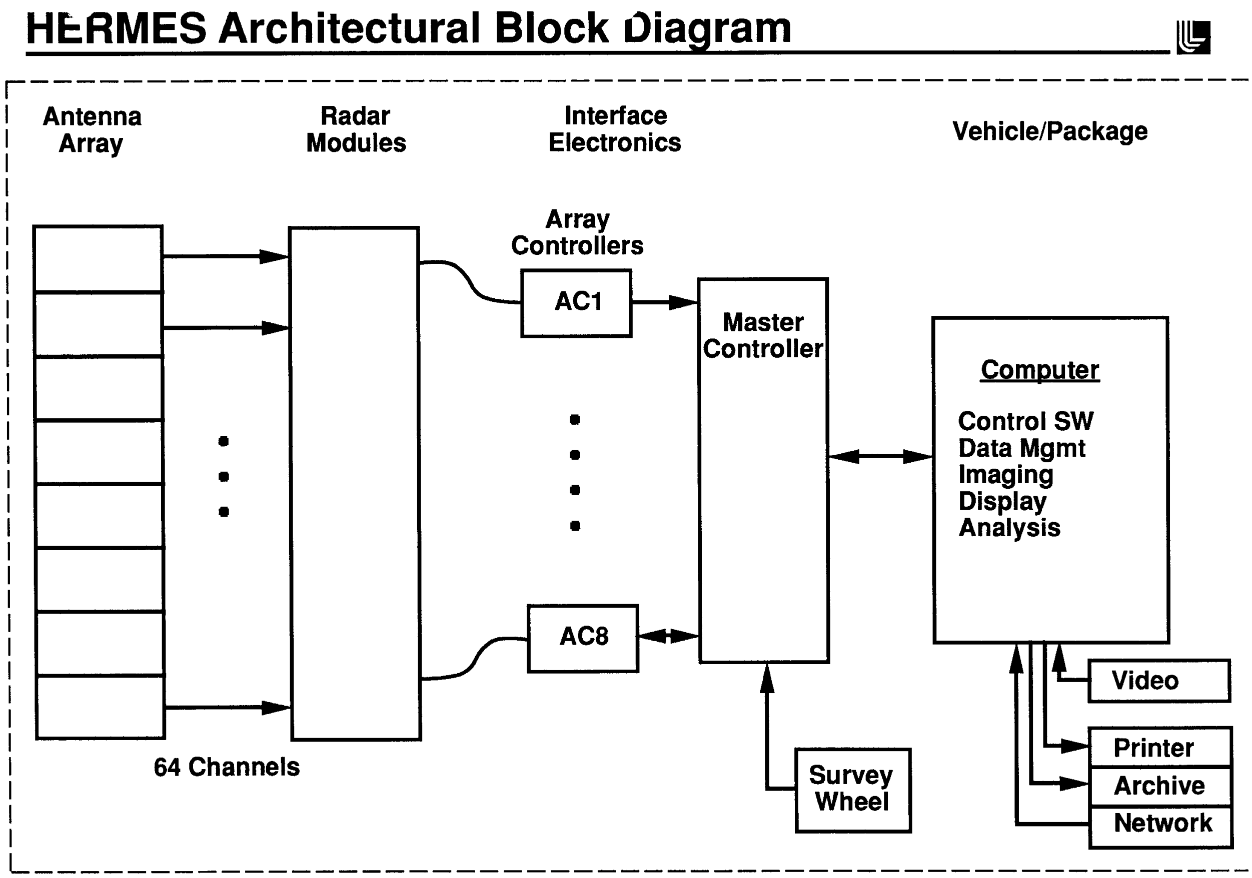

Fig. 3. Block diagram of the HERMES radar system.[3]

The most important design feature of the HERMES is the antenna array. The array consists of eight banks of eight transceivers, totaling 64 channels, housed within a 2.1 by 2.1 m frame. Each pair of transmit and receive antennas is skewed at 45° to the axes of the frame. Therefore, the emitted polarized radiation gives rise to reflections of equal magnitude from transverse and longitudinal features such as steel reinforcement bars. The arrangement of the transceivers gives samples across a 1.9 m width of the deck at 3 cm intervals; in the direction of movement 3 cm spacing or less, is also attainable. The density of data enables synthetic aperture radar (SAR) techniques to be used in the processing of the data. As data is taken over a 1.9 m wide swath 3D reconstructions of the deck interior may be computed. This is preferable to recording data along one or more displaced survey lines which yields 2D profiles along the paths of the transceivers.

Sampling at 3 cm in the direction of movement is attainable up to 20 mph. Increases in speed are possible with a reduction in the rate of data acquisition over the array. Operation at 60 mph is achievable with 6 cm measurement spacing and half the number of equivalent-time samples. Either half the time-range, or double the time-interval would have to be chosen dependent on whether resolution or depth of penetration was important.

2.2 Description of the PERES bridge inspector

The PERES bridge inspector consists of a single transceiver mounted on a computer controlled robotic cart. An illustration of PERES is shown in Fig. 4. The transceiver is moved across the surface of the road along a rail which is fixed perpendicular to the direction of cart movement. As the transceiver is moved along the rail data is collected at regular points. PERES then moves forward a set interval while the transceiver returns to it's original location. The process is repeated until the required area of the bridge deck has been surveyed.

Fig. 4. The PERES bridge deck inspection system.

As the survey speed of PERES is relatively slow, and there is only a single antenna pair, there is sufficient time to collect numerous samples at each location over the road surface. Approximately 100 samples are collected and averaged over at each interval in time and therefore random noise is reduced. Thus the data from PERES is of a higher quality, higher effective signal to noise ratio, than that of the HERMES.

The sampling interval along the rail may be varied, as can the distance PERES moves between sweeps of the transceiver. A spacing between measurements of 1 cm is possible when high horizontal resolution is required. Moving the transceiver at such small intervals and with the precision granted by the robotics gives data over a grid far more accurate than is possible with a surface-coupled hand-held transceiver. Having data over a well defined grid facilitates the SAR processing techniques. Therefore, images are made available which visualize the internal structure in a more realistic way than the original data.

3. PRELIMINARY TRIALS AND RESULTS

An initial test of HERMES and PERES has been performed across two bridge decks in northern California. These bridges were suitable for evaluating the performance of the radar systems as they were about to be rehabilitated. The planned renovation included the removal of the deck and therefore 'ground truth' information would become available. Coring was carried out after the radar surveys to correlate the returned signals with knowledge of the internal structure. On dismantling the bridge, sections of the deck were also removed for further correlation and more tests.

3. 1 HERMES tests

Scans of the deck were conducted towing the HERMES trailer across the bridge deck at approximately 5 mph. The system was calibrated to determine the delay time to be introduced so that the desired window in time was sampled. The delay was set to 4 ns two-way travel time so that data was collected to approximately 20 cm thick depths within the concrete.

An example of original data obtained from one element of the antenna array is given in Fig. 5. The data relates to a vertical section through the reinforced concrete deck in the direction of the roadway. The length of the displayed section is approximately 6 m. The most evident feature contained within the data is the series of hyperbolae produced from the reinforcement. The explanation for the hyperbolae is the dispersed nature of the radar beam which leads to reflections being received from point targets before the antenna is directly over it and after the antenna passes over.

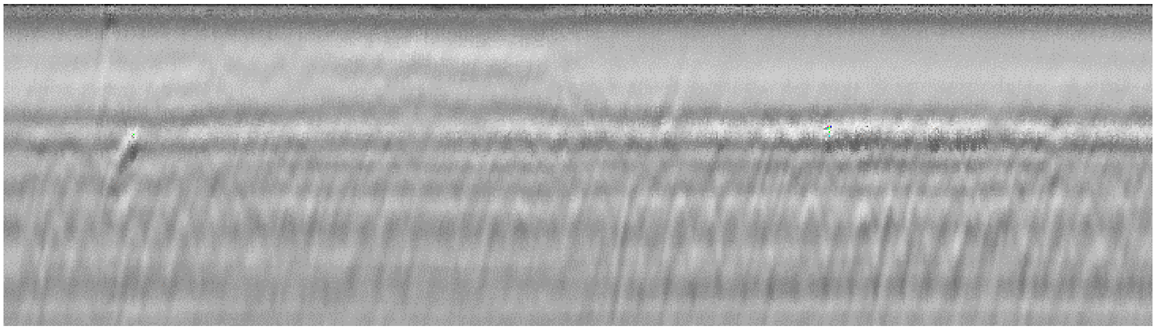

Fig. 5. Original data from one antenna of the HERMES array.

A SAR reconstruction program, utilizing multi-frequency diffraction tomography,[12] was then applied to this data to produce an image more representative of the true structure. Fig. 6 displays the data after reconstruction. The hyperbolae of Fig. 5 are no longer evident in this profile. The reconstruction program has focused the hyperbolae tails back to their sources, i.e. the location of the reinforcement crossing the survey line. There are numerous spots of high reflectivity, the white areas, which are partly due to the positions of the reinforcement. However, some may be due to voids within the deck and some may be artifacts of ringing in the radar pulse and not physical features of the interior. Additionally some zones of the deck appear to reflect more energy than others suggesting some change in the dielectric constant and conductivity of the concrete. Interpretation of the radar plots will be investigated in the future evaluation of the system.

Fig. 6 A 2D vertical reconstruction of the HERMES data of Fig. 5.

3.2 PERES tests

Testing of PERES concentrated on areas of the two bridges which were thought to be of most interest in the investigation of deterioration within the bridge. SAR reconstructions of an area of bridge deck is displayed in Fig. 7 and 8. Fig. 7 shows an image of a horizontal plane 7.3 m by 1.5 m through the deck while Fig. 8 is a representation of a 20 cm thick vertical cross-section cutting through the length of the area.

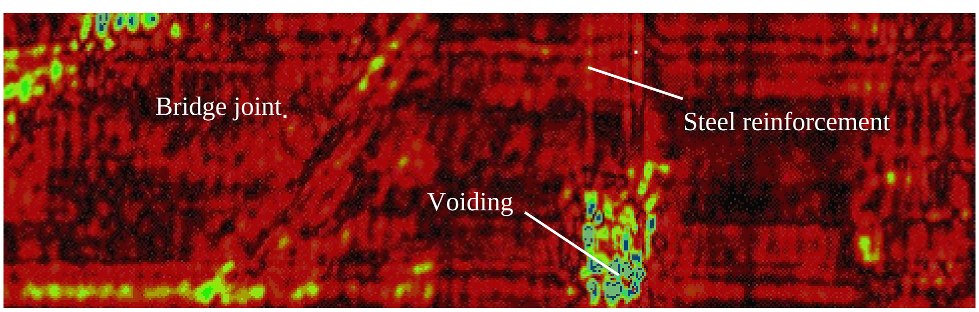

Fig. 7. Reconstructed PERES data showing a horizontal plane through the reinforced concrete deck.

These figures indicate the presence of reinforcement, location of a bridge joint and some anomalous areas which were speculated to be voids. Cores of the anomalous zones found that there were indeed voids in the concrete at these locations.

Additionally cores in areas which did not show anomalous reflections did not locate voiding. 3D rendered views of this deck section were also produced.

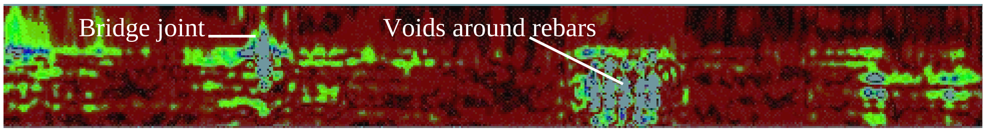

Fig. 8. Vertical cross-section reconstruction of PERES data.

There are, however, a number of questions to be addressed in the interpretation of the data. As for the data collected with the HERMES, Figs. 5 and 6, the PERES data also shows areas of high reflectivity, where the reinforcement is well defined, and areas of low reflectivity in which it is difficult to locate the position of reinforcement.

3.3 Summary

Initial trials of the HERMES and PERES have been undertaken under field conditions. The HERMES system has demonstrated the ability to produce vertical 2D reconstructions of the data collected from a single antenna at a towing speed of approximately 5 mph. The data indicates the location of reinforcement and areas which appear to be of different reflectivity, implying some physical change in the properties of the concrete.

Tests with PERES have produced 2D, horizontal and vertical, and 3D SAR images which led to the location of voids within a concrete bridge deck. The PERES single transceiver system eliminates much of the processing steps which are needed to prepare the HERMES data for horizontal 2D and 3D reconstructions. However, data processing software is under development for this purpose.

4. FUTURE TESTING AND DEVELOPMENT

The future evaluation of the systems will consider how effective the radar systems are in the determination of structural detail and construction and corrosion related deficiencies. The physical features under investigation include delaminations, asphalt thickness, asphalt/concrete disbond, steel reinforcement location, debonding between reinforcement and concrete, honeycombing and voids. The ability to detect these structural components and defects will be considered in relation to the following variables: depth within the deck, separation between the features (resolution, vertical and horizontal), presence of water, temperature and towing speed (HERMES). The time for data collection and processing will also be assessed.

An NDE Validation Center[2] is to be set up at Turner-Fairbank Highway Research Center (TFHRC) and the concrete specimens and bridge sections at this facility will be used for evaluating the systems. Once experience has been gained at the validation center and on local bridges, tests at sites farther from TFHRC will be conducted. Then the system performance in different environments and for the application to problems not found in the nearby bridge stock will be investigated. Demonstrations to State DOT’s will also take place.

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